Biomimetic compound eye with a high numerical aperture and anti-reflective nanostructures on curved surfaces

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Biomimetic compound eyes with a high numerical aperture on a curved surface were successfully fabricated by intelligent integration of traditional top-down and bottom-up micro- and nanofabrication methods together. In addition, the new hybrid micro- and nanofabrication method allows us to fabricate the antireflective nanostructures on each ommatidium to increase its vision sensitivity by improving the light transmission. The fabricated compound eye was optically characterized and was shown to have a numerical aperture of 0.77 for each ommatidium. Furthermore, it is shown that the transmission of the compound eye can be improved by 2.3% for the wavelength of 632.8 nm and a clearer image can be formed by the fabricated compound eye with antireflective nanostructures compared with that without antireflective nanostructures. In addition, the developed hybrid manufacturing method can be adapted to the fabrication of other complex micro- and nanodevices for photonics or other research areas.

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Biomimetic compound eyes have attracted great attention for their potential applications in the fields of biology, optoelectronics, and military because of their unique optical properties, such as large field of view (FOV), fast image-processing capability, and the fast tracking of moving objects [1–10]. Traditionally, planar lithographical methods are employed to fabricate microlens array-based compound eyes on flat surfaces; therefore, it is difficult to obtain compound eyes with large FOV and high numerical aperture [4,11,12]. Recently, Lee *et al.* [9] reported the fabrication of compound eyes on curved surfaces, which provides a possible way to fabricate compound eyes with a FOV of up to 180 deg. More recently, Joung [13] reported the fabrication of artificial ommatidia on curved surfaces by laser direct writing. In all of these works, however, the numerical aperture of the fabricated ommatidium is always no larger than 0.5, and therefore, its imaging capability is limited in terms of resolution. In this work, a biomimetic compound eye on a curved surface was successfully fabricated by intelligent integration of traditional top-down and bottom-up micro- and nanofabrication methods. In addition, the new hybrid micro- and nanofabrication method allows us to fabricate the antireflective nanostructures on each ommatidium of compound eyes to further increase its light transmission.

Figure 1 provides the schematic of the fabrication process developed within this work. The fabrication begins with a microlens array, which was fabricated by a traditional photolithographic process and the following photoresist reflow process at a temperature slightly higher than its T_g of 115 °C as shown in Fig. 1(a). The fabricated microlens has a diameter of 700 μm and a height of 60 μm. Each spherical surface of the microlens acts as a curved substrate for ommatidia in the following process. To realize the ommatidia on the curved substrate, a self-assembled method was employed. In cases in which the microlens curved substrate was horizontally dipped into the solution as shown in Fig. 1(b), the polystyrene (PS) microspheres with a diameter of 25 μm then were self-assembled in a monolayer honeycomb hexagonal form on the interface of the air and the deionized water, and finally, the substrate was moved up perpendicularly to allow the PS microspheres to rest on the curved surface of the substrate automatically with a close-packed hexagonal form retained as shown in Fig. 1(c). Thus, the compound eyes on the curved substrate were formed with PS microspheres as ommatidia. To realize the antireflective nanostructure on compound eyes, the self-assembled method again was employed. It is found, however, that the PS nanospheres are difficult to rest on the PS microspheres surface. Therefore, the compound eyes need to be replicated in other polymers that are suitable for PS nanospheres to rest. Here, the soft-lithography method was employed to transfer the compound eye microstructure into a UV-curable epoxy resin (NOA 68, Norland Products Incorporated, Cranbury, NJ) as shown in Figs. 1(d)–1(f). After replicating the compound eye microstructure into epoxy resin, the PS nanospheres with a diameter of 190 nm were self-assembled onto the compound eyes surface as shown in Figs. 1(g) and 1(h). The self-assembled PS nanosphere monolayer acts as an antireflective surface because of its deep subwavelength lattice constant feature, and therefore, it can improve the light sensitivity of the ommatidia significantly.

On the basis of the fabrication process summarized in Fig. 1, the compound eyes with and without antireflective surfaces were successfully fabricated. Figures 2(a) and 2(b) show the images of the fabricated compound eyes with a different scale taken by an optical microscope, whereas the inset picture of Fig. 2(b) shows the self-assembled nanospheres on the microsphere taken by an electron-scanning microscope. As seen in Fig. 2(b), the microspheres are well organized together by a self-assembled method. The hexagonal sides between the microspheres are clearly visible, which indicates that the

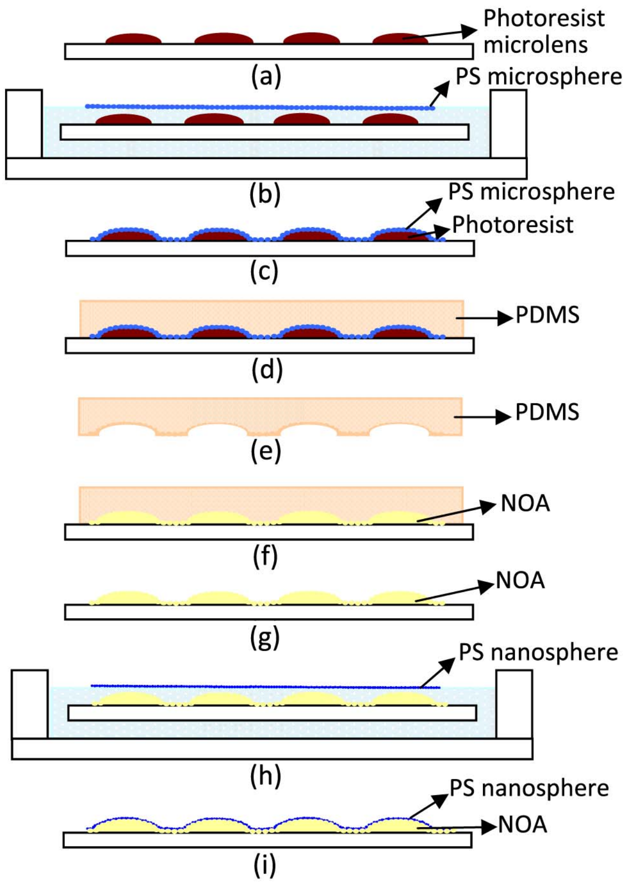

Fig. 1. (Color online) Hybrid top-down and bottom-up micro- and nanofabrication methods for the fabrication of biomimetic compound eye with antireflective nanostructure surface. (a) Microlens curved substrate fabricated by photolithographic process and photoresist reflow process; (b) and (c) fabrication of compound eyes through self-assembled method; (d)–(g) soft-lithograph process for the replication of compound eye in UV-curable epoxy resin; (h) and (i) fabrication of antireflective nanostructure on compound eyes surface by self-assembled method.

plane interface between microspheres has been formed during the assembled process. Although, in theory, the microspheres should contact each other by points, we attribute this effect to the solvent having dissolved the contacting surface between microspheres during the capillary forceinduced interaction.

In addition, it is found that the numerical aperture of the formed ommatadia can be tailored by annealing the self-assembled microspheres on the photoresist curved surfaces for a period of variant time at an elevated temperature that is a bit higher than the glass transition temperature of the photoresist. In this case, the microspheres would sink into the photoresist polymer so that the numerical aperture of the formed ommatadia becomes smaller. This occurs because the density of the PS microsphere is far larger than that of the photoresist. It should be noted as well that the PS microsphere melt on the photoresist due to its T_g (about 97 °C) is lower than the annealing temperature. Understanding why the molten microsphere can still retain its ball shape and does not flow down or mix with photoresist involves complex chemical knowledge and is still not understood. As shown in Fig. 3, the valid diameter of the ommatidium reduces from around 22 μm to around 17 μm when annealing time changes from 1 min to 5 min. The sinkage of the microsphere into the polymer becomes severe, however, when annealing time extends to 10 min, and some microspheres almost sink into the polymer as shown in Fig. 3(c). Because the sinkage of the microsphere into the polymer will affect the numerical aperture of the ommatidium significantly, the annealing time should be controlled carefully to achieve the desired numerical aperture of the ommatidia.

To characterize the optical property of the fabricated compound eye, the point spread function of the compound eye was tested. Figure 4 shows the optical setup used for the characterization of the compound eye. An He–Ne laser with a wavelength of 632.8 nm was used as the light source with the laser beam collimated and deflected onto the compound eye by a 45 deg mirror. A 1000× optical microscope was used to capture the focal points of the compound eye. Figure 5 shows the measured image of the point spread function of the fabricated compound eye and the inset top-right picture shows the enlarged point spread function of one ommatidium. As shown in Fig. 5, the smallest light spot, i.e., Airy disc of the ommatidium, has a size of about 1 μm, which means the resolving power of each ommatidium is around 1 μm. According to the diffraction theory, the numerical aperture of the ommatidium is around 0.77 for the wavelength of 633 nm. Considering the natural compound eye normally has a numerical aperture of less than 0.3 for each ommatidium, the numerical aperture of our fabricated compound eye represents a twofold improvement in performance and provides a higher resolution. Considering each ommatidium is formed by replication of a 25 μm diameter sphere into the Norland UV-cured polymer with a refractive index of 1.56, a numerical aperture

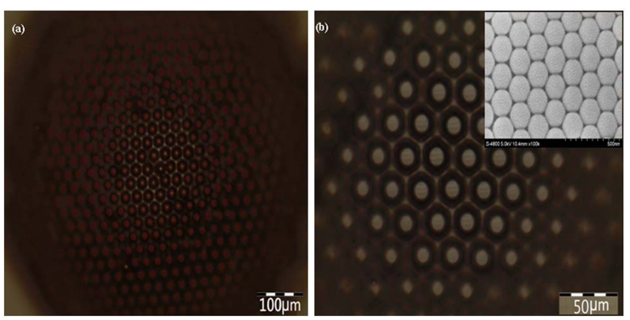

Fig. 2. (Color online) Images of the fabricated artificial compound eye taken by microscope.

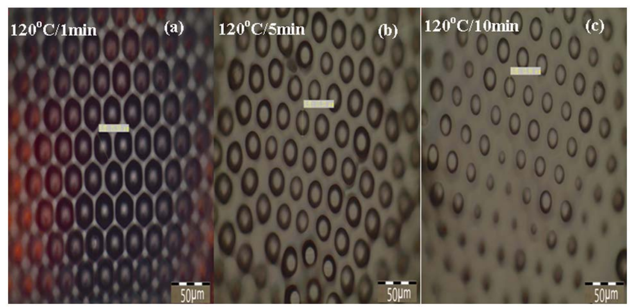

Fig. 3. (Color online) Annealing of the self-assembled microspheres on curved surfaces for a period of variant time at an elevated temperature of 120 °C.

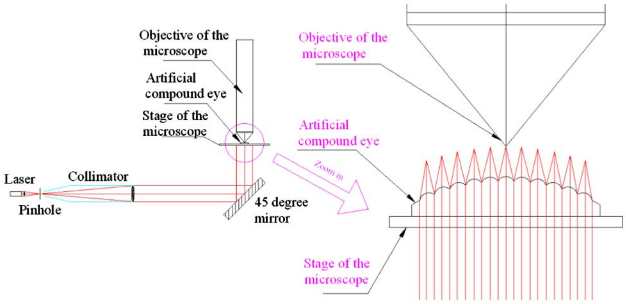

Fig. 4. (Color online) Optical setup used for the measurement of the point spread function of the compound eye.

of 0.77 means that the ommatidium is more than a hemisphere, i.e., the sagittal height of the ommatidium must be larger than 12.5 μm (the radius of the PS sphere). The light spots at the edge of the FOV are a little bit larger because those spots were captured at the defocal position, which also means that the ommatidia are located on the curved surface but not on the flat surface.

To further characterize the imaging property of the fabricated compound eye, the eye was used for the imaging of a photomask. The photomask has a pattern of circular arrays with a diameter of 100 μm. The fabricated compound eye was placed on the top of the photomask and an Olympus optical microscope was used to capture the image taken by compound eyes. Figure 6(a) shows the photograph of the photomask imaged by the fabricated compound eye. As can be seen, the image of the circle array has been formed by every ommatidium of the compound eye. The diameter of the image of each circle is around 6.51 μm, which means a demagnified image has been formed because the objective distance is far greater than twice as great as the focal length of the ommatidium. By employing the paraxial geometrical optics imaging theory and some simple algebra, it is not difficult to derive that the height of the ommatidium is 24.93 μm, which is nearly equal to the diameter of the curvature of the ommatidium. Thus, we can conclude that the ommatidium is actually a spherical ball microlens. In this case, the numerical aperture of the ommatidium can be calculated to be 1.53, which is nearly double that obtained from the point spread function measurement result. We attribute this great deviation to the feature of micro-optics in which diffractive optics plays a more important role than geometrical optics and the paraxial approximation assumption in geometrical optics is no longer valid.

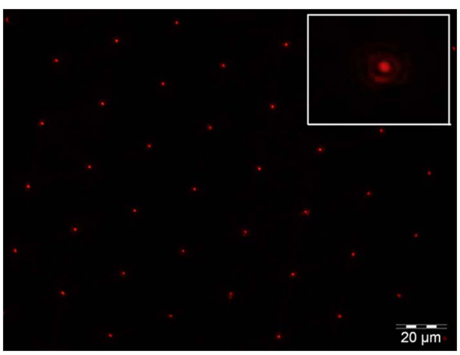

Fig. 5. (Color online) Point spread function of the fabricated compound eye measured by optical method.

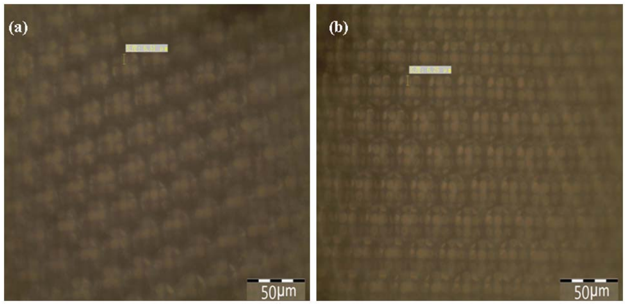

Fig. 6. (Color online) Photograph of the image of a circle array with a diameter of 100 μm for each circle formed by the fabricated compound eye (a) without and (b) with antireflective nanostructures.

Finally, to demonstrate the antireflective property of the self-assembled nanospheres, the light transmission of the compound eye with antireflective nanostructures was measured and a 2.3% enhancement in transmission for the wavelength of 632.8 nm was obtained. In addition, its imaging property was characterized. Figure 6(b) shows the photography of the image of a circle array with a diameter of 100 μm for each circle formed by the fabricated compound eye with antireflective nanostructures. Compared with the image of Fig. 6(a) formed with the compound eye without antireflective nanostructures, the image formed by the compound eye with antireflective nanostructures is a little bit more clear. This means that the antireflective nanostructures enhance the light transmission to some extent.

In summary, we have successfully developed and demonstrated the fabrication of the biomimetic compound eye by uniquely combining the top-down microfabrication method with the self-assembled bottom-up micro- and nanofabrication methods. The fabricated compound eye has an even higher numerical aperture when compared with those archived by other researchers. Finally, the biomimetic compound eye with antireflective nanostructures was fabricated and its light transmission was measured to be higher than that without antireflective nanostructures.

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